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Quantitative guidance on how best to respond to a big nuclear accident

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ABSTRACT

A review is made of the quantitative methods used in the NREFS project (Management of Nuclear Risks: Environmental, Financial and Safety) set up to consider how best to respond to a big nuclear accident. Those methods were: the Judgement- or J-value, optimal economic control and a combination of the computer codes PACE and COCO2 produced at Public Health England. The NREFS results show that the life expectancy lost through radiation exposure after a big nuclear accident can be kept small by the adoption of sensible countermeasures, while the downside risk is less severe than is widely perceived even in their absence. Nearly three quarters of the 116,000 members of the public relocated after the Chernobyl accident would have lost less than 9 months' life expectancy per person if they had remained in place, and only 6% would have lost more than 3 years of life expectancy. Neither figure is insignificant, but both are comparable with life expectancy differences resulting from the different day-to-day risks associated with living in different parts of the UK. It is clear in hindsight that too many people were relocated after both the Chernobyl and the Fukushima Daiichi accidents. Remediation methods can often be cost-effective, but relocation of large numbers following a big nuclear accident brings its own risks to health and well-being and should be used sparingly, a message coming from all three of the quantitative methods. There is a need to understand and hence demystify the effects of big nuclear accidents so that decision makers are not pressurised into instituting draconian measures after the accident that may do more harm than good.

1. Introduction

It is nearly 75 years since the world's first self-sustaining nuclear fission process was demonstrated at Stagg Field, Chicago, and nuclear power is now a significant component of the world's electricity supply. 435 nuclear power plants are operating worldwide, located in 30 countries, while 72 new nuclear plants are under construction in 15 countries. Nuclear power plants provided 12.3% of the world's electricity production in 2012, with 13 countries relying on nuclear energy to supply 25% or more of their total electricity (Nuclear Institute, 2014). However the severe reactor accident at Chernobyl in 1986 caused 335,000 members of the public to be relocated permanently away from their homes while 25 years later 160,000 people were instructed to relocate or moved away voluntarily after the accident at the Fukushima Daiichi nuclear power plant. These are huge numbers without industrial precedent, and raise the question of how far they were justified and, more generally, how should one cope with a big nuclear accident, should it occur in the future?

This question raised above formed the focus for the NREFS research project (Management of Nuclear Risks: Environmental, Financial and Safety). The project was sponsored by the Engineering and Physical Sciences Research Council (EPSRC) as part of the UK-India Civil Nuclear Power Collaboration, and involved 4 universities: City, University of London, Manchester University, The Open University and the University of Warwick. The author, who was Principal Investigator, was based at City, University of London throughout the duration of the NREFS project before taking up his current position with the Safety Systems Research Centre of the University of Bristol in 2015.

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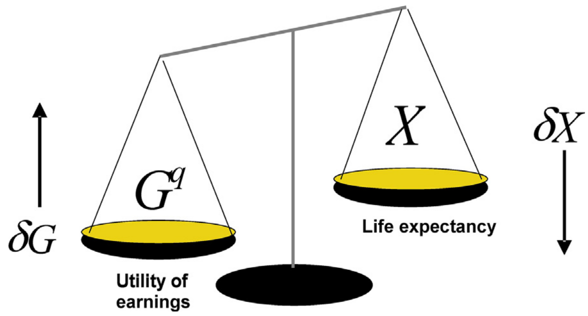

Fig. 1 – Balancing the utility of earnings against life expectancy.
(G^q is the (power) utility of earnings, G, where $q = 1 - \varepsilon$ in which ε is risk-aversion).

This paper reviews the methods used to generate answers to the questions raised above, and summarises the main findings first presented in outline form to the All-Party Parliamentary Group on Nuclear Energy on 11 March 2015 (NREFS, 2015). Three diverse methods point towards the conclusion that while big nuclear accidents are undoubtedly bad things, the radiation harm to the public is significantly less severe than is widely perceived, even in the worst cases. The fact that the downside risk is much less than is widely feared should reduce the pressure on decision makers. They should thus find themselves in a better position to take rational decisions as a result, and resist the temptation to institute draconian precautionary measures that may do more harm than good.

2. Methods of assessment

It is a requirement of Article 16.1 of the Convention on Nuclear Safety (International Atomic Energy Agency, 1994) that coping strategies for big nuclear accidents should be developed in advance, a stance that is reinforced by experience at both Chernobyl and Fukushima Daiichi. But any mitigation strategy adopted in practice will find itself in the spotlight of national and world opinion, and needs to be capable of rigorous justification, not only to experts in the field but also to politicians and the general public, who are widely presumed to have a particular fear of nuclear radiation, especially in the context of industrial nuclear power.

The use of subjective techniques to support mitigation strategies is immediately problematical, since judgements made by one group will almost inevitably clash with judgements made by another. This puts a premium on making the methods used for guidance and decision making in relation to such accidents as objective as possible, since these can offer the potential for wide acceptance.

Three quantitative methods were used in the NREFS project:

- the J- or Judgement-value method (Thomas et al., 2006a,b,c), which achieves objectivity and impartiality through balancing any future radiation-induced loss of life expectancy against the amount it is rational to spend on averting or reducing the exposure, as illustrated diagrammatically in Fig. 1. Appendix A summarises the J-value method, which was validated against pan-national data during the course of the project. It uses actuarial and economic parameters, all objectively measurable, to throw new light on the problems of relocation, food bans and remediation.
- optimal control, which follows the approach developed by Richard Bellman (Bellman, 1952, 1954, 1957). It was applied in the NREFS project to a model of the dynamic process of ground contamination after a major nuclear accident, with the model elements shown in diagrammatic form in Fig. 2. The extended system includes dynamic equations to describe the three broad countermeasures, food bans, remediation and population movement (relocation and repopulation), that constitute the control variables assumed available to the authorities.
- the combination of the Level 3 program, Probabilistic Accident Consequence Evaluation (PACE) described in Charnock et al. (2013) with version 2 of the Cost of Consequences computer program, COCO2 (Higgins et al., 2008). Both computer codes were developed at Public Health England (PHE).

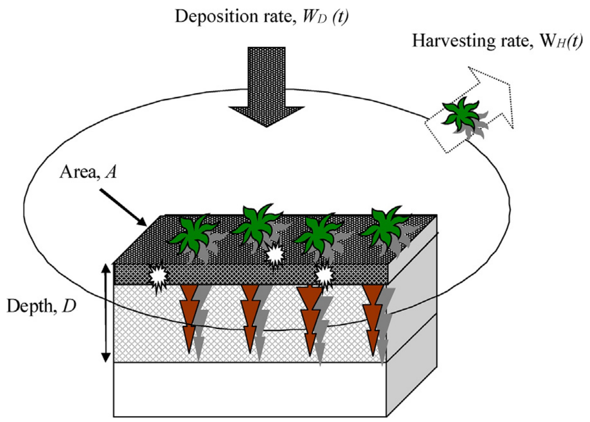

Fig. 2 – Showing radio-nuclide deposition, growth of vegetation and harvesting, either directly or via animal feeding.

Despite coming at the problem from diverse viewpoints, the three methods produced results that show significant commonality. Taken together, they reinforce the message that governments have tended to overreact if and when a bad nuclear reactor accident occurs, with the attendant offsite releases of radioactivity. Such an overreaction goes against the first and most fundamental of the three key principles of radiological protection, namely the Principle of Justification:

> "Any decision that alters the radiation exposure situation should do more good than harm" ICRP (2007).

Clearly the analyses of the Chernobyl and Fukushima Daiichi accidents have been made with the benefit of hindsight and there is no intention to blame the authorities for their responses in those cases. Nevertheless there are lessons to be learned from those accidents which should be applied in the management of a future big nuclear accident, should it occur.

3. Major findings of the NREFS project

3.1. *Relocation*

Relocation is taken to mean living away from a designated exclusion zone for a substantial time (many months or a year or more), after which return to the original location starts to become problematical. Staying away for a prolonged period will reduce both social and occupational ties to the original location and has been found to engender a general reluctance to return. It has a meaning distinct from 'evacuation', which is carried out in hours or over a day or two and is not expected to last for long, often for less than a week and not usually more than a month or so.

Fig. 3 – Profile of doses in future years relative to Year 1 dose.

The major finding is that, while some temporary evacuation might be reasonable during the time in which the size of the radioactive release is being confirmed, very often it will be sensible not to adopt a policy of large-scale relocation, even after a big nuclear accident with significant radioactivity release.

The results of the three, diverse quantitative methods used in the NREFS study are given below under the appropriate subheadings:

- J-value,
- optimal economic control and
- Public Health England's PACE-COCO2 program suite.

3.1.1. *J-value*

The J-value results suggest that even the first relocation in 1986 of 116,000 people from the vicinity of Chernobyl was an overreaction. The J = 1, maximum permissible loss of life expectancy per person was calculated at 8.7 months for the economic and actuarial conditions of the Soviet Union in 1986. It was then possible to determine the corresponding radiation dose profile that would reduce by 8.7 months the life expectancy of a person selected at random from amongst those so exposed. Here the task was to find the appropriate scaling for the radiation decay curve shown in Fig. 3. On this basis it is estimated that 31,000 relocated persons (26.5%) needed to be relocated (Waddington et al., 2017a) since staying in situ would expose them to a higher dose profile and hence a greater curtailment in life expectancy, based on population dose data from UNSCEAR (2000) and UNSCEAR (2008). A loss of life expectancy above 8.7 months would mean that the average person would judge it worthwhile in terms of his or her overall life quality to pay the cost of relocation and avoid the dose and associated reduction in life to come. In terms of Fig. 1, a gain of more than 8.7 months would tip the scales in favour of relocation. (The person would not normally expect to bear the relocation cost personally, but his/her willingness to do so is regarded as an appropriate criterion in welfare economics for judging compensatory expenditure.)

The number to be relocated rises to 72,500 if it is assumed that the 31,000 cannot be easily identified, and precautionary relocation of the whole village or town is instituted if the worst-affected 5% of the inhabitants are calculated to lose 8.7 months or more. The countermeasure will thus exceed what is needed by 95% of the people living in the affected towns and villages. But even if the higher figure is adopted, this still implies that relocation was not a suitable policy choice for over a third (43,000) of the number relocated in 1986.

The number of people moved in Chernobyl's second relocation four years after the accident was roughly double the size of the population relocated in 1986. But the J-value suggests that none of the 220,000 people in the second relocation of 1990 ought to have been moved from their homes. Life quality for those concerned, as measured by the Life Quality Index (Nathwani and Lind, 1997; Nathwani et al., 2009; Thomas et al., 2006a,b, 2010a), was being reduced as a result. This conclusion confirms the finding of a study requested from the European Community by the USSR and carried out contemporaneously with the second relocation (Lochard and Schneider, 1992; Lochard et al., 1992). Unfortunately their findings were not taken up by the Soviet authorities, arguably creating a precedent for the policy of very large-scale relocation as a matter of course after a major nuclear accident.

Taking the two Chernobyl relocation exercises together, in 1986 and 1990, Waddington et al. (2017a) conclude that while relocation of the members of the public under the highest threat after Chernobyl would have been advisable in 1986, the total number of people eventually relocated should have been only between 9% and 22% of the final figure of 335,000. This implies that at least a quarter of a million people were moved away from the Chernobyl area without proper justification.

160,000 people were relocated after the 2011 accident at Fukushima Daiichi, but the J-value analysis suggests it is difficult to justify the relocation of even those facing the most elevated radiation dose (Waddington et al., 2017a). Thus, after examining the two biggest nuclear reactor accidents that have been observed, the conclusion coming from the J-value studies is that relocation ought to be used sparingly if at all.

The J-value provides an objective criterion against which the reasonable extent of health and safety expenditure can be judged, something that is especially valuable when payment is to be made by a third party, such as an industrial company or government. The J-value might indeed be useful to a person considering whether or not to relocate voluntarily, but clearly no restriction should be placed on the freedom of individuals to move under their own volition.

3.1.2. *Optimal economic control*

Broad corroboration for the J-value conclusion on the desirability of restraint in the deployment of relocation as a policy option comes from a diverse study using optimal economic control (Yumashev and Johnson, 2017; Yumashev et al., 2017). Wide ranges of economic parameter values (including allowance for the health effects of radiation) are used in that work to explore which optimal strategies might be applicable to nuclear reactors situated throughout the world. Commonalities amongst these schemes are then brought out through classifying the optimal approaches into "Broad Strategies". Examination of the Broad Strategies reveals that relocation forms no part of the optimal strategy for any combination of economic parameter values in the Base Case (or Case I, to use an alternative terminology).

Two variants to the Base Case are considered: Case II, where relocation is imposed immediately after the accident, thus excluding that action from the optimisation process, and Case III, where there is a reversal of the Base Case assumption that lower economic productivity awaits those moving from the original to the new area. Permanent relocation is ruled out in the very large majority of the optimal strategies associated with either Case II and Case III.

The optimal economic control study concludes that relocation is likely to be a less than optimal response after very many major nuclear accidents.

3.1.3. PACE-COCO2 program suite

The general trend towards evacuating relatively low numbers and relocating permanently a much smaller number is given broad confirmation in a further diverse study using Public Health England's PACE-COCO2 program suite. A fictional nuclear power station is taken to be located on England's South Downs, about 2½ miles from Midhurst in Sussex, and is assumed to experience a severe reactor accident leading to a release of radionuclides comparable in size to that at Fukushima Daiichi (Ashley et al., 2017). Such a bad accident is projected to happen no more than once in ten million years on a modern reactor.

Two intervention levels, “lower” and “upper”, were considered in choosing the mitigation strategies to be applied to the areas around the stricken South Downs reactor, with the upper intervention level requiring the dose to be averted to have reached a higher point before intervention could be justified. While the adoption of the lower, more interventionist level leads to a 25% reduction in the number of non-fatal cancers attributable to radiation effects, there is a difference of only a few percentage points between the two intervention levels in terms of the numbers calculated for fatal leukemias and solid cancers.

The expected number of people needing immediate, temporary evacuation after this accident at the fictional South Downs reactor is 44,000 when the lower, more interventionist level is applied, but this number falls to 1500 when the upper intervention level is employed. Temporary relocation (lasting up to 90 days) could affect 12,000 people, but these should be able to return to their original dwellings at the end of the three-month period. Only 620 people are expected to need permanent relocation. Such a level of permanent relocation is based on the rather strict return criterion, applied three months into the accident, that the radiation dose to be received over the following 12 months at the original location should be 10 mSv or less.

To put 10 mSv per year into context, this level of dose, year on year, has been found in over 40,000 homes surveyed in the UK, and is expected to be present in a further 60,000 British dwellings as a result of the in-seepage from the ground of naturally occurring radioactive radon gas (Parliamentary Office of Science and Technology, 2001). To quantify the associated level of harm, a dose of 10 mSv per year for 50 years is calculated, on the basis of the linear, no-lower-threshold model, to reduce the life expectancy of a typical person in the affected population in the UK by about four and a half months. In reality, the radiation dose after a nuclear reactor accident would be falling significantly, both between 3 months and 15 months and thereafter, in the way shown in Fig. 3 (Waddington et al., 2017a). This graph is based on the radioactive decay of the two caesium isotopes that dominate the dose to humans in the medium and longer term, namely ^{134}Cs (half-life 2.01 y) and ^{137}Cs (30.2 y).

3.1.4. General comments

The results from the three methods described above take no account of the further negative effects (dislocation and stress) likely to be caused by the relocation process, especially when the number of people relocated is a hundred thousand or more. In fact, the process of relocation itself is known to have a directly negative impact on the health and life expectancy of those concerned. Over 1000 evacuees died prematurely as a result of the evacuation process at Fukushima Daiichi (World Nuclear Association, 2015). In a detailed analysis of the evacuation of three nursing homes following the accident at Fukushima Daiichi, Murakami et al. (2015) found that a combined total of roughly 10,000 days or 27½ years of life expectancy were lost by the nursing home residents as a result of a hasty evacuation. Deleterious psychological and sociological effects have also been observed after the mass relocations following Chernobyl:

> “Evacuation and relocation proved a deeply traumatic experience to many people because of the disruption to social networks and having no possibility to return to their homes. For many there was a social stigma associated with being an ‘exposed person’.” (World Health Organization, 2016)

These findings reinforce the message that relocation should be used sparingly following a severe nuclear reactor accident.

3.2. *Remedial measures: agricultural and urban*

3.2.1. J-value

The J-value was used to assess remediation measures taken after Chernobyl, which took the form of both urban decontamination and agricultural measures to reduce the ingestion of radioactive contamination. The latter included removing vegetation, ploughing, liming, fertilization and reseeding, as well as the application of ferrocyn to cattle feed to reduce the uptake of caesium and hence its transfer to humans via milk and meat. Assessment using the J-value showed that many urban decontamination measures were justifiable after the accidents at both Chernobyl and Fukushima Daiichi. Moreover, the J-value was able to provide not only a ranking but an objective quantification of the degree of economic effectiveness of each countermeasure. In general terms, remediation emerged as a worthwhile option, although it would be necessary to check the cost-effectiveness in each case using the J-value (Waddington et al., 2017b).

3.2.2. Optimal economic control

Under optimal economic control, local food production might need to be brought to a halt in the immediate aftermath of a big nuclear accident, but it would be returned to normal levels typically within 2–2½ years.

3.2.3. PACE-COCO2 program suite

The PACE-COCO2 model of the South Downs reactor accident calculates that the expected value of lost agricultural production would be £130 M. The total cost of the accident could be expected to be £800 M but there is a 1 in 20 chance that it could reach £2.8 bn, not including the cost to the electric utility company of decommissioning the stricken reactor, nor of replacing its electricity generation capability.

3.3. *Control of sheep meat in the UK following the Chernobyl accident*

It is clear with hindsight that the authorities overreacted with their relocation policy at Chernobyl and that the same thing happened at Fukushima Daiichi. But the governments of the USSR and Japan were not alone in the exaggeration of their response. Based on J-value analysis, it is now clear that the UK authorities adopted a strategy with regard to sheep meat on the Cumbrian, Welsh and Scottish uplands after Chernobyl that was, at least by the end, too precautionary.

Restrictions were imposed in 1986 on the movement, sale and slaughter of sheep on 9700 farms in North Wales, Cumbria, Scotland and Northern Ireland. The number of restricted farms was reduced over the years, so that by 2010 only 300 farms remained in this restricted category. But the restrictions on Welsh and Cumbrian lamb imposed after Chernobyl were not lifted for these farms until 2012, when their cost was at least an order of magnitude too much as they increased life expectancy of UK citizens by seconds only, a gain that must lie below the *de minimis* level in any case (Waddington et al., 2017c). Keeping them in place for 26 years constituted an over-reaction to Chernobyl.

The NREFS project did not have the resource to investigate how long the restrictions on sheep meat should have been kept in place before being terminated, nor, indeed, whether it was sensible to impose them in the first place. But such a J-value study could be expected to produce useful results to guide future policy.

3.4. *Life expectancy as a measure of harm*

As discussed in Waddington et al. (2017a), medical professionals are seeking a better way of understanding the risk from nuclear radiation both for their own information and so that they can communicate an accurate picture to the people in their care who look to them for impartial advice. Calculated as a matter of course in the application of the J-value method, the radiation-induced loss of life expectancy is itself an information-rich statistic that is nevertheless easy to understand. Moreover, loss of life expectancy is the best single indicator of what is lost when someone dies prematurely (Thomas and Vaughan, 2013). Thus, even in the absence of a J-value, the loss of life expectancy may offer medical professionals and others a good comparative measure with which to explain levels of risk to lay people and professionals alike.

Take, for example, the situation after the Chernobyl accident in 1986. The expected life to come for people of all ages in the Ukraine was about 35 years in 1986, with the corresponding life expectancy at birth being about 67 years. (For comparison, the current figures for the UK are about 42 years and 81 years respectively.) The application of the Change of Life Expectancy After Radiation Exposure (CLEARE) program, with actuarial data appropriate for the Soviet Union in 1986 (Waddington et al., 2017a), shows that that 73.5% (85,500) of the 116,000 people relocated from around Chernobyl in 1986 would have lost less than 8.7 months of life expectancy per person if they had remained in situ, with an average loss of about 3 months. 8.7 months is, of course, the $J = 1$ loss of life expectancy, above which the J-value method would recommend relocation. About 6800 people, 6% of those relocated in 1986, would have lost 3 years or more if they had not been relocated. The average dose received by these worst-affected 6800 people would have cost them 5.6 years of life expectancy per person in the absence of relocation.

None of these figures, 3 months, 8.7 months, 3 years and 5.6 years, is insignificant, and the J-value prescribed relocation in the former Soviet Union when the loss of life expectancy per person exceeded 8.7 months. But even the highest two figures may be put into a degree of context as a result of their similarity to the differences in life expectancy resulting from the different day-to-day risks associated with living in different parts of the UK. Thus the average person living in Harrow in London can expect to live about 3¼ years longer than the average person domiciled in Manchester (based on the 6½ years difference in life expectancy at birth across the two genders (ONS, 2015) and the life expectancy ratio (population average life expectancy ÷ life expectancy at birth) of roughly 0.5 for the UK (Thomas and Waddington, 2017a,b)).

Even the highest of the figures cited, a loss of life expectancy of 5.6 years in the absence of relocation, is less than the difference, 8.6 years, in life expectancy of baby boys born in Kensington and Chelsea and of those born in Blackpool (ONS, 2015). These comparisons do not make the case for inaction, since, by the J-value, relocation should have been instituted for any loss of life expectancy greater than 8.7 months per person after the Chernobyl accident. But it is suggested that they do promote a quantitative understanding of the size of the radiation risks to the public living nearby after the worst nuclear reactor accident the world has experienced.

A second evacuation was effected at Chernobyl four years after the event in 1990, in which 220,000 people were relocated permanently. The average dose for the 900 people living in the most contaminated areas and relocated in 1990 (less than 0.5% of the 220,000 moved out then) would have led to a loss of life expectancy of 3 months if they had remained in place. This is two thirds of the roughly 4½ months life expectancy that the average Londoner is currently losing because of air pollution (based on the 9 months loss of life expectancy at birth cited in Darzi (2014) and the life expectancy ratio of 0.5 mentioned in the paragraph above).

3.5. *The loss of life expectancy due to a radiation induced cancer*

The losses of life expectancy discussed in Section 3.4 will apply to a population or sub-population, most of whom will not contract a radiation induced cancer and will thus lose no years of life at all. So the question is raised of how great is the loss of life expectancy amongst those destined to be radiation cancer victims, even if fortunately there are likely to be few of them.

The situation of radiation exposure was represented using a simple but physically meaningful model, in which those exposed were subject either to a constant radiation dose rate over time or to a "point" exposure, profiles that bracket the falling dose profile shown in Fig. 3 that is characteristic of public exposure after a big nuclear reactor accident (Thomas, 2017). It is found that the average radiation cancer victim will live into his or her 60s or 70s, depending on how long the radiation exposure lasts, based on data from the UK life tables. Between 8 and 22 years of life expectancy will be lost on average by a radiation cancer victim. The calculational method adopts the linear, no-threshold model recommended by the International Committee on Radiation Protection (ICRP), but the result is independent of both the size of the risk coefficient and the size of the annual dose, provided the dose is below the level where it causes acute radiation syndrome (radiation sickness and, in extreme cases, death).

The fact that the highest average loss of life expectancy due to a radiation induced cancer is 22 years is striking, since this is only about half the loss of 42 years that an immediately lethal accident, such as a car crash, would bring about. Thus averting a radiation induced cancer brings only about half the benefit accruing from averting an immediately fatal railway or automobile accident. Such a comparison is fully relevant under the view, held very widely in society and, indeed, enshrined in law, that life is preferred to death. It should be borne in mind, too, that the long latency period of radiation-induced cancers means that most of the two decades of extra life that the average radiation cancer victim gains over the fatal car crash or rail crash victim can be expected to be lived normally, with living becoming restricted, with an attendant eventual need for palliative care, only near the end of the period.

This would suggest that people ought to be prepared to pay out about twice as much on systems to avert immediate deaths on the railways or in cars as they would to avert delayed, radiation-induced cancer deaths. Interestingly, this runs directly counter to the current stance of the Health and Safety Executive (HSE), as enunciated in their document, “Reducing Risks, Protecting People: HSE’s decision-making process”:

> “Currently, HSE takes the view that it is only in the case where death is caused by cancer that people are prepared to pay a premium for the benefit of preventing a fatality and has accordingly adopted a VPF twice that of the roads benchmark figure. Research is planned to assess the validity of this approach.Äppendix 3, paragraph 13 (HSE, 2001).

Objectively, the HSE would seem to have got it the wrong way round. The result calls into question the concept of the Value of a Prevented Fatality (VPF) that is still recommended by the UK Government on a “one-size fits all” basis. Further profound problems exist with the figure used for UK VPF, as discussed in Appendix B.

3.6. *Validating the J-value method*

The paper by Thomas and Waddington (2017a) tests the validity of the J-value method against international observations of life expectancy and GDP per head, and finds that the J-value passes the test and is able to explain the findings. The J-value-based model made the following assumptions:

(i) the annual budget available to prolong citizens’ life expectancy is a fixed fraction of gross domestic product (GDP) per head,

(ii) the budget is spent in full each year under the constraint that the J-value associated with life-extending decisions is unity,

(iii) the value of risk-aversion applicable to decisions on life extension remains constant as wealth and life expectancy increase in tandem and is thus the same for all nations in the world. (Risk-aversion, while corresponding closely to the concept as used in ordinary language, benefits from a rigorous mathematical definition; see Thomas (2016))

(iv) the net discount rate applied to life expectancy remains constant as wealth and life expectancy increase in tandem.

The resulting J-value-based model is able to explain the variation in population-average life expectancy with GDP per head, as plotted on logarithmic axes. Named the “Bristol curve” after the city where the two authors were working (Thomas and Waddington, 2017a,b), this locus complements the Preston curve with which Preston (1975) highlighted the positive correlation between national GDP per head and life expectancy at birth (Fig. 4). With an R^2 value of 0.80 when applied to 162 out of the 193 nations recognised by the UN, the J-value model is able to explain 80% of the variation in the logarithm of population-average life expectancy in terms of the variation in the logarithm of GDP per head. An extension of the J-value model is able to give what is believed to be the first theoretical explanation for the Preston curve. It is predicted correctly that moving from the Bristol to the Preston curve will cause the characteristic risk-aversion to fall by about 5% on average. The log–log version of the Preston curve is then explicable with an almost identical R^2 value, 78%, for the 162 countries.

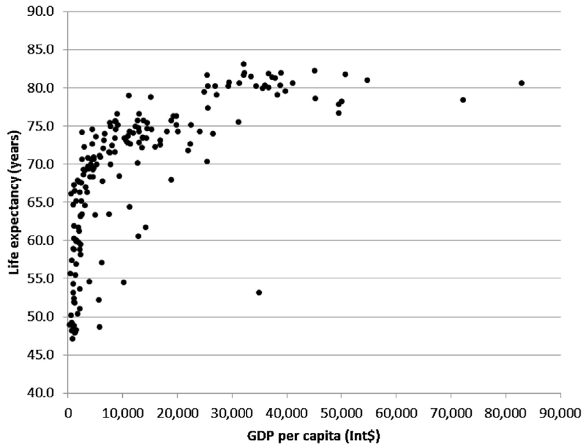

Fig. 4 – The Preston curve — life-expectancy at birth (years) as a function of GDP per capita (international dollars) for the 180 countries for which both datasets are available for 2009.

The Bristol curve results are corroborated by an independent method whereby the previous derivation of the value of risk-aversion (Thomas et al., 2010a) is extended to include an allowance for the employee enjoying his/her time at work half as much as his/her leisure time (as opposed to not enjoying working time at all). As a result, decisions concerning extension of life made by a person in a developed country emerge as being subject to a risk-aversion, 0.91, that is about 10% above the value of 0.82 derived from examining the trade-off that people in the UK make between free time and working time (Thomas et al., 2010a).

The J-value-based model just described has been further tested in a different role, namely the prediction of future life expectancy at birth within a given country. Its success in this task with a risk-aversion of 0.91 for the UK and other economically advanced countries provides additional validation for the J-value concept (Thomas, 2017a). The J-value’s success in these validation exercises stands in stark contrast to the deficiencies uncovered in the method currently used in the UK to value human life, as explained in Appendix B.

The J-value approach emerges as essentially a formalisation of an approach being used intuitively all over the world to assess most health and safety spending decisions. Its value lies in making judgements objective and consistent as well as transparent, thus providing a level playing field for improving safety across all human activities, from nuclear through oil and gas, chemicals and transport through to the provision of health services (Thomas, 2017b).

4. Discussion

Few would dispute that anxiety about radioactive fallout after a major nuclear reactor accident is one of the great fears of the age (see, for example, Nuttall and Ashley, 2017). Certainly when prompted, people will express a high level of concern or dread of nuclear radiation, especially if it is associated with industrial nuclear power (e.g. Ropeik, 2013). The NREFS project has surveyed the evidence available from the world’s two biggest nuclear reactor accidents and examined how far such fear is justifiable. Quantitative methods were used in the investigation, with the new J-value technique deserving a special mention, as it was validated against empirical data during the course of the NREFS study, conferring high credibility on J-value assessments as a result.

NREFS made a detailed analysis of the aftermath of the Chernobyl accident in 1986, where the core went super-prompt critical during, ironically, a safety experiment. The top was blown off the reactor, the core melted through the bottom of the reactor pressure vessel and a fire raged out of control for 10 days, during which time large amounts of radioactive material escaped unhindered into the atmosphere. It is difficult to see how the situation on the nuclear reactor could have been much worse, and there is no disagreement that Chernobyl represents the worst nuclear reactor accident the world has seen to date.

30 plant personnel and firefighters died in the immediate aftermath of the Chernobyl accident and the 116,000 members of the public considered to be most at risk were relocated permanently in 1986. However the J-value analysis suggests that only between 31,000 and 72,500 people should have been relocated after the Chernobyl accident, depending on the specificity of the measurements and the accompanying estimates of radiation dose. A second relocation of double the size was carried out 4 years after the accident, but the J-value analysis suggests that it was not justifiable to uproot any of the 220,000 moved from their homes in 1990, a conclusion shared with an authoritative study carried out contemporaneously for the European Community at the request of the USSR (Lochard and Schneider, 1992; Lochard et al., 1992).

Even if the short-term evacuation advised by the Japanese authorities may have been justified while the situation clarified, the J-value results suggest that, given the Japanese Government's $20\,\mathrm{mSv\,y^{-1}}$ safe-return criterion, it was not advisable to relocate any of the 160,00 people actually relocated after the accident at Fukushima Daiichi in March 2011, even those facing the highest increase in exposure above natural background levels. Taken together, the Chernobyl and the Fukushima analyses suggest that relocation of people should be regarded as a countermeasure to be used sparingly if at all after a major nuclear accident (although obviously no restriction should be replaced on voluntary relocation).

It should be noted that the detailed conclusions drawn concerning the post-accident management at Chernobyl and at Fukushima benefit from hindsight and, more specifically, from data that would have been more extensive than those available in the immediate aftermath. Moreover, the numerical results cited for the J-value depend on measurements of ground contamination over large regions near the Chernobyl and Fukushima Daiichi reactors and on models of the behaviour of radiation-emitting radionuclides making up that contamination, including radioactive decay and migration into the human food chain. While there will, inevitably, be scope for inaccuracy in both the model and the measurements, nevertheless confidence in the results is generated by the commonality in the overall conclusions coming from the other two, diverse approaches, namely optimal economic control and PACE-COCO2.

The same general trend against mass relocation following a major nuclear accident emerged from the PACE/COCO2 study, where a core-damage accident at a fictional reactor located in Sussex was examined. Only about 600 people were marked out for permanent relocation even when a strict return condition was used, a figure in marked contrast to the more than 100,000 people displaced after both Chernobyl and Fukushima accidents. Meanwhile relocation of a large population played no part in the dominating fraction of economically optimal strategies for medium-term recovery after a major nuclear reactor accident (Yumashev et al., 2017).

In retrospect, it is clear that decision makers faced with the immediate and longer-term aftermath of the world's two most severe nuclear reactor accidents did not always make the best decisions in their attempts to protect the lives and well-being of the people under threat.

It is desirable that the performance of future decision makers facing a similar situation should be enhanced by providing better information and decision support mechanisms. As a minimum, further development is indicated both for the spatially distributed measurement systems needed to produce real-time readings of the quantities of radionuclides deposited in the areas around a stricken nuclear power plant and for the models needed to translate those measurements into current and future doses for the people living in the surrounding towns and villages. The doses may be either direct or come via agricultural produce, but will diminish over time as the level of radionuclides declines as a result of radioactive decay and natural environmental processes. These long term transients need to be modelled accurately at the various locations. The information on dose profiles at multiple locations can then be fed into the decision-support programs (J-value, optimal economic control) that should be developed to make their results available in real time to the decision maker. Clearly similar support mechanisms ought to be provided at all the world's reactors.

The importance of communicating the risk from nuclear radiation in a realistic but easily understood manner has been flagged by Japanese medical professionals, to whom the public has looked for impartial advice after the Fukushima Daiichi accident. While the J-value allows an objective balance to be struck between reducing radiation-induced loss of life expectancy and expending resource on a given countermeasure, the information-rich statistic of radiation-induced loss of life expectancy, which is a component of J-value analysis, could fulfil an important role in communicating how big or small the radiation risk is. It encapsulates the best, unbiased quantification of what someone loses by dying prematurely and provides a continuous scale for judging the severity of the risk from radiation. Importantly, once calculated the change in life expectancy is simple to understand. The basic meaning will be taken on board easily by most people, who gain familiarity from their earliest years with the concept of personal age through marking and often celebrating their birthdays.

The clear worth of loss of life expectancy as an aid to understanding just how big or small is the threat to the general public after a big nuclear accident is brought out by applying it to the populations of Ukraine and Belarus following the Chernobyl accident. Although the harm to some people living near Chernobyl would have been significant if they had stayed in place, a comparison with the differences in life expectancy in different parts of the UK shows that the level of harm following a severe reactor accident, even in the absence of relocation, is almost certainly not as significant as many people believe.

There is no doubting that a severe nuclear accident is a very bad thing and strong efforts should continue to be made to ensure that it happens very infrequently. However, the message emerging from the figures on loss of life expectancy and the desirable extent of relocation is that the downside risk from even the worst nuclear accident can be calculated and is likely to be limited. Knowledge of this fact will hopefully put decision makers in a better position to take sensible decisions and prevent them being pressurised by exaggerated fears into rushing out draconian precautionary measures that may well cause more harm than good.

The evidence emerging from NREFS is, unfortunately, that the draconian actions taken by the respective governments after Chernobyl and Fukushima may well have done more harm than good. Others have concluded similarly. For example, the World Health Organisation (WHO), in conjunction with the International Atomic Energy Agency and the United Nations Development Programme, said in 2005 that, after Chernobyl:

> "mental health problems pose a far greater threat to local communities than does radiation exposure.
>
> "Relocation proved a 'deeply traumatic experience' for some 350,000 people moved out of the affected areas. Although 116 000 were moved from the most heavily impacted area immediately after the accident, later relocations did little to reduce radiation exposure.
>
> "Persistent myths and misperceptions about the threat of radiation have resulted in 'paralyzing fatalism' among residents of affected areas." (WHO, 2005a)

The three organisations just mentioned enlarged upon their comments on the response to Chernobyl in the section entitled, "Answers to Longstanding Questions" (WHO, 2005b):

> "More than 350 000 people have been relocated away from the most severely contaminated areas, 116 000 of them immediately after the accident. Even when people were compensated for losses, given free houses and a choice of resettlement location, the experience was traumatic and left many with no employment and a belief that they have no place in society. Surveys show that those who remained or returned to their homes coped better with the aftermath than those who were resettled. Tensions between new and old residents of resettlement villages also contributed to the ostracism felt by the newcomers. The demographic structure of the affected areas became skewed since many skilled, educated and entrepreneurial workers, often younger, left the areas leaving behind an older population with few of the skills needed for economic recovery."
>
> and
>
> "According to the [Chernobyl] Forum's report on health, 'the mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date.' People in the affected areas report negative assessments of their health and well-being, coupled with an exaggerated sense of the danger to their health from radiation exposure and a belief in a shorter life expectancy."

The fact that this message was promulgated widely by a respected body over ten years ago raises the question as to why Ropeik (2013) as well as Nuttall and Ashley (2017) (and many more) should believe that people still look with dread upon the health effects of radiation after a major nuclear accident. There seem to be two reasons for such dread. The first relates to the last point in the quotation immediately above, namely the shorter life expectancy that people fear that they will be left with if their area is contaminated by nuclear fallout after a reactor accident. The truth is that, up until now, few radiation experts have attempted to address this fear head on. This can be done only by stating how much life expectancy the affected people are likely to lose. Fortunately, as a result of the NREFS work, it is now possible to calculate directly how much life expectancy will be lost, both for those relocated and for the same people if they had stayed in situ.

The doses experienced by the 116,000 people moved out in the first relocation after Chernobyl can be calculated to have led to an average loss of less than 2 weeks' life expectancy, caused by the residual higher dose that they faced. This is self-evidently a rather small loss. Equally striking is how much they would have lost if they had stayed in situ, with no evacuation and no relocation. As noted in Section 3.4, the average loss of life expectancy for nearly three-quarters of the 116,000 people relocated would have been about 3 months if they had stayed in place, with the average loss of life expectancy exceeding 3 years for only about 7000 of the 116,000 people, based on dose estimates used in Waddington et al. (2017a). While it has been shown desirable to evacuate people set to lose 9 months of life expectancy or more, it needs to be borne in mind that the penalties arising from leaving people in place are still comparable with differences in life expectancy incurred from the day-to-day risks of normal living in different parts of a highly developed country like the UK.

The people affected by the nuclear accident will not know in advance whether or not they will be personally affected by the increased risk of a radiation-induced cancer, and this makes the average loss of life expectancy across non-victims and victims discussed above the appropriate measure to use in the first instance. But those same people will almost certainly want to have some idea of the likely downside if they should turn out to be a radiation cancer victim, that is to say one of the small number of people who will, unfortunately, die prematurely as a result of contracting a radiation induced cancer. It turns out that even here there are grounds for encouragement, in the sense that the average radiation cancer victim will live past the age of 60, based on UK life table data and the Marshall model of radiation cancer mortality period, the period between induction and death. Moreover, the average loss of life expectancy is, at between 8 and 22 years, about half at most of the loss of life expectancy associated with an immediately lethal accident, such as a fatal road or rail crash.

The variances associated with the figures just quoted are high, and the situation is generally worse for a young person compared with an older person. But even for someone who is both very young at the time of the accident and also one of those unfortunately destined to contract a radiation-induced cancer, the loss of life expectancy is highly likely to be at least 15 years less than that following involvement in a fatal road accident as a very young person. (See Thomas, 2017, Fig. 15, "Age at death for radiation cancer victims with a starting age of zero".) For prolonged radiation exposures the mean age at death climbs to over 60 years, even for those facing an increased radiation level from birth.

But now we come to the second reason why people are likely to fear radiation exposure after a big nuclear accident: neither they nor their governments have been able to put the risk properly into context. While the loss of life expectancy is an important and information-rich statistic, it does not do the whole job. It turns out that, in judging any probabilistic risk, such as the chance of harm from radiation, it is necessary to consider not only the expected harm but also the expected cost of averting that harm. This has now become possible and may be effected using the validated J-value method, which allows the balance point to be found at which life quality, as given by the life quality index, is just maintained. Spending up to that point is then justified, but it is not desirable to spend more.

In the past, and specifically after both the Chernobyl and Fukushima Daiichi accidents, it is clear with hindsight that the national governments became too risk-averse *to that particular risk* and embarked upon exaggerated actions and spending. As noted in WHO (2005b):

> "The costs have created a huge drain on the budgets of the three countries involved [Ukraine, Belarus and Russia]."

which will have inhibited desirable public spending elsewhere. It has been further demonstrated theoretically (Thomas et al., 2010b,c; Thomas and Jones, 2010) that it is not a sensible thing for a decision maker to increase his risk-aversion beyond a definable point, the "point of indiscriminate decision", after which decisions take on an arbitrary character. What appears to have been lacking generally is not the willingness by governments to become ever more risk averse when faced with a nuclear hazard and to sanction very large expenditures in consequence, but the realisation that it is not a good use of public money to spend excessively to reduce the particular risk from radiation. As has now been shown, even after the world's worst nuclear accident, the level of risk experienced by the public in the absence of countermeasures is not out of line with the differences in the risks of everyday living seen in an advanced country.

Comfort might be sought in the thought that the governments concerned with Chernobyl and Fukushima Daiichi will, by overspending on support for those most affected, at least have provided very substantial help to the people whose health they were attempting to improve. But the evidence for this proposition is not convincing. The World Health Organisation (WHO, 2005a,b) has pointed to relocation being traumatic and leading to unemployment and a feeling of worthlessness amongst those relocated. Moreover, as noted above, WHO (2005b) comments that the people affected have "an exaggerated sense of the danger to their health from radiation exposure and a belief in a shorter life expectancy".

The last point provokes the question of exactly why those relocated should believe that the small radiation dose that they will have received just before moving (and perhaps, at a lower level, after they have done so) should have shortened their lives by any significant amount. Some illumination can be provided here by the J-value. Most people can be expected to have little feel for radiation and still less with the effect on life expectancy that any given radiation dose is likely to cause. On the other hand, he or she can be expected to have a good feel for the enormous expenditure involved in relocating a hundred thousand people or more and in abandoning huge swathes of farmland. Moreover, as has been shown by the validation studies (Thomas, 2017a; Thomas and Waddington, 2017a,b), people generally have a feel for the balance between the desirability of life extending measures in general and the money that should sensibly be paid on such measures. In terms of the J-value model, one side of the equation is known and well understood, and this known can now be employed to work out the remaining unknown, namely the degree of harm caused by the radiation received. To be sure, the normal use of the J-value is to assess measures taken to reduce or avert exposure to harm, but it could equally be used to assess how much ought to be spent in compensation. Suppose that the relocated people saw what was being spent on them not as a way of protecting them from harm but as a way of compensating them for the damage that has been or is being inflicted on them. Will they not now effectively back-calculate[1] the extent of their harm from the vast expenditure that they observe and should they not therefore conclude, in all rationality, that the likely harm they are facing is enormous, and that they are almost sure to die much earlier than they would have done if the accident had not happened? Is it not now fully rational for those who have been relocated to see themselves as victims, almost certain to die young? The Chernobyl Forum has testified that many of those relocated after Chernobyl have come to this logical conclusion, from which further deleterious effects have flowed:

> "The designation of the affected population as 'victims' rather than 'survivors' has led them to perceive themselves as helpless, weak and lacking control over their future. This, in turn, has led either to over cautious behavior and exaggerated health concerns, or to reckless conduct, such as consumption of mushrooms, berries and game from areas still designated as highly contaminated, overuse of alcohol and tobacco, and unprotected promiscuous sexual activity." (WHO, 2005b)

So the overspending after a big nuclear accident in the name of protection is immediately and inevitably compromised by the indirect but very real harm that the very act of overspending causes.

It is clear that decision makers facing a big nuclear accident ought to be engaging what Kahneman (2011) has described as "system 2" or analytical thinking in performing their duties, rather than the knee-jerk "system 1". But this is presumably the general situation in which many decision makers with heavy responsibilities find themselves. The hope must be that dissemination of the NREFS results may start a gradual process by which the need for such "system 2" thinking with regard to big nuclear accidents becomes more broadly accepted as a replacement for the "system 1" approach that has been evident so far.

5. Conclusions

The NREFS project has applied diverse, quantitative methods to the problem of coping with the aftermath of a big nuclear accident. The three different methods display a significant degree of commonality in their results and highlight the need for restraint on the part of decision makers contemplating relocation.

The performance of decision makers facing a large-scale nuclear reactor accident can be improved by the provision of better decision support mechanisms such as J-value and optimal economic control. It is advisable to develop real-time versions of these, together with the necessary radionuclide measurement and modelling systems, for application at all

[1] It is not being suggested that people are actually performing J-value calculations in their heads, only that the J-value provides a good model for the amount that people are prepared to spend on life extending measures. Regarding such socio-economic models, the U.S. political scientist, Bueno de Mesquita (2009) summed up the situation clearly when he said: R̈eal people may not be able to do the cumbersome math that goes into a model, but that doesn't mean they aren't making much more complicated calculations in their heads even if they don't know how to represent their analytic thought processes mathematically."

reactors around the world in preparation for big nuclear accidents that may never happen in the future but have happened twice in the past 30 years.

However, a big lesson from NREFS is that there are limits to the radiation damage likely to befall members of the public, after even the biggest nuclear reactor accidents. Most of the harm from the world's worst two nuclear reactor accidents is likely to have come from what can now be seen to be largely unjustified fear and worry and from the social disruption and dislocation caused by the relocation of hundreds of thousands of people.

Excessive spending on the supposed protection of the members of public most affected after a big nuclear accident may well do more harm than good. Not only might it constitute a waste of valuable resources, but it might well harm the very people it is intended to help. Convinced by the scale of the expenditure that they must be the victims of a terrible scourge, their mental and physical well-being may suffer severe and self-fulfilling damage.

It is therefore very important that the relatively limited effects of even big nuclear accidents should be understood better and thus demystified. The dissemination of the results of the NREFS project, both to decision makers and to the general public, could begin that process.

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Appendix A. Summary of the J-value method

The J-value provides an objective assessment tool which can be applied across all industries. It is a new technique based on the life quality index (Nathwani and Lind, 1997; Nathwani et al., 2009), but it makes use of established economic theory. The method has the considerable advantage when compared with other approaches such as conventional cost benefit analysis, that no explicit assumptions have to be made about the difficult issue of the monetary value to be attached to saving a human life. Also, unlike other approaches, the J-value allows immediate fatalities and potential loss of life in the longer term (e.g. when the hazard includes exposure to a carcinogen), to be measured on the same scale. Ways to reduce risks can then have their cost effectiveness assessed fairly.

The J-value balances safety spend against the extension of life expectancy it brings about. At the core of J-value is the concept of the life-quality index, placing a monetary value on all future years of life based on GDP per head, using an empirically measured value of risk-aversion that allows the utility of average income in the nation to be determined. The J-value is found by dividing the actual cost of the safety measure by the maximum that it is reasonable to spend. A value of less than one indicates that the expenditure is fair. A value greater than one suggests that spending resources may not be justified.

The objective decision is then simple. If the J-value is much more than one, the starting point for any decision is that the resources should not be committed to reducing this risk. If it is less than one, there is a strong case for spending the money.

Appendix B. Problems with the Value of a Prevented Fatality (VPF) used in the UK

When considering how best to respond to a big nuclear accident, a comparison between the cost of a safety measure and the benefit that it produces becomes a necessary part of the analysis. The J-value is a fully objective way of carrying out this comparison (e.g. Waddington et al., 2017a,b,c). However, the conventional way of valuing human life in the UK is through using the "value of a prevented fatality" (VPF), which is the maximum notionally reasonable to pay for a safety measure that will reduce by one the expected number of preventable premature deaths in a large population. Given its wide endorsement in the UK, an examination was made of the validity of the UK VPF.

There is an immediate problem with the VPF, since it is assumed to be the same for all people in the UK, irrespective of age; this in itself must be regarded as a highly questionable assumption: does a 20 year old lose the same thing as a 90 year old if he or she is killed in an accident? Furthermore the VPF does not recognise a distinction between a threat of imminent demise and threats where death, if it occurs, will be delayed for decades, two very different things. Nevertheless the VPF figure, updated to account for changes in gross domestic product (GDP) per head, has been used extensively in the UK for the past 17 years as a reference not only by Government departments but also by the Health and Safety Executive (HSE) in judging how much should be spent on protection measures aimed at reducing risks to life.

However, Thomas and Vaughan (2015a) found multiple failures in tests of the validity of the two-injury chained method used to interpret results in the Carthy study (Carthy et al., 1999) on which the UK VPF is based (Department for Transport, 2014). Chilton, Covey, Jones-Lee, Loomes, Pidgeon and Spencer attempted to defend their work (Chilton et al., 2015) but admitted that that their method led to systematic errors, that it had undoubted limitations, that it needed more research and that their VPF was reliant on the exercise of the authors' own judgement. Thomas and Vaughan (2015b) replied to this defence, judging that the significant reservations they had expressed concerning the Carthy study and its methods remained entirely valid. Two of the original six authors ventured a second defence of the Carthy study (Jones-Lee and Loomes, 2015) but this was rebutted in full in Thomas and Vaughan (2015c), where it was concluded that the VPF derived from the two-injury chained method was unsubstantiated and demonstrably not fit for purpose. A recent review of the UK VPF by Thomas and Waddington (2017b) provides a summary of the multiple problems afflicting the UK VPF.

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